Lunar Architecture Affordability Assessment

Integrating Architecture, Programmatic, and Affordability Viewpoints

Robert Shishko and Joseph Mrozinski
Jet Propulsion Laboratory
California Institute of Technology

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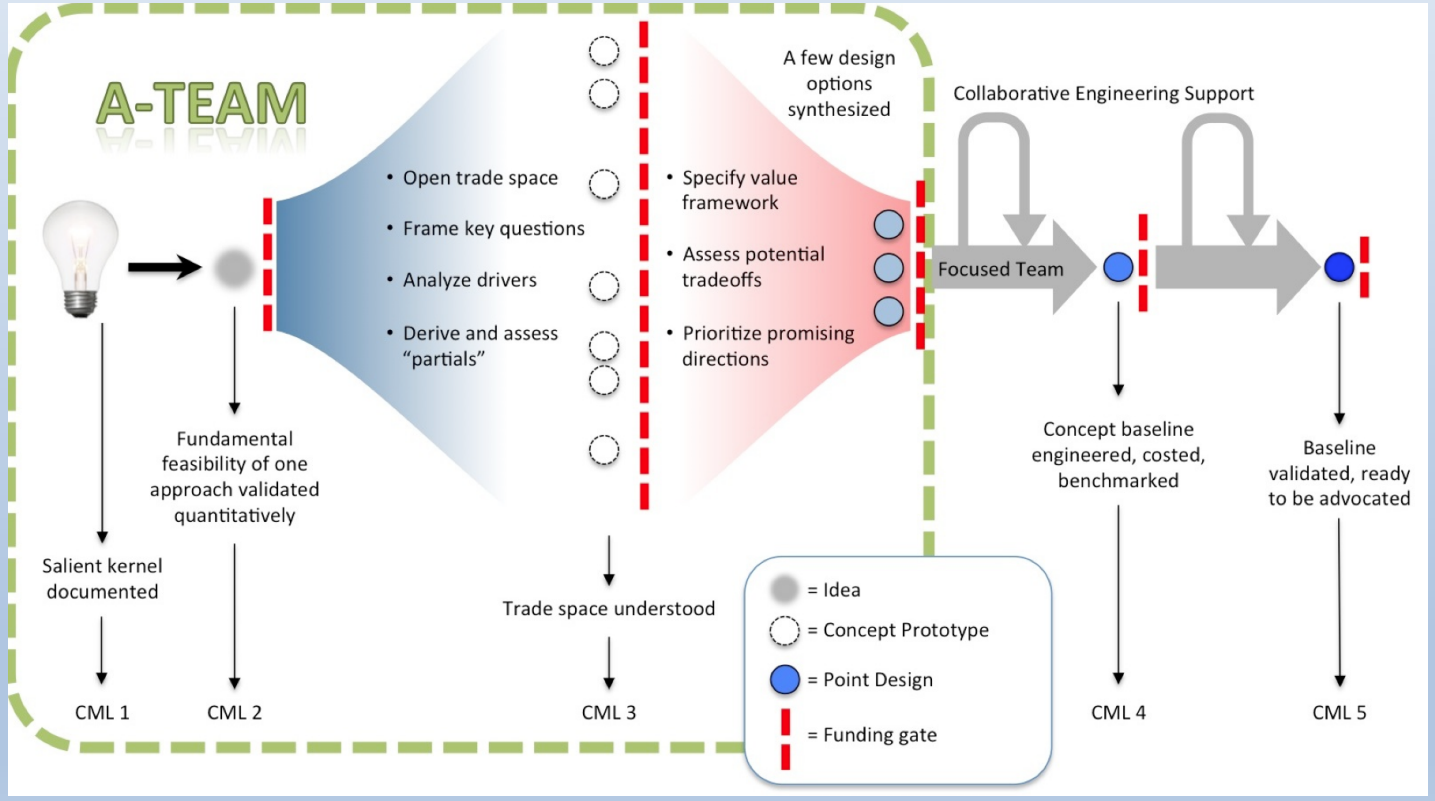
A-Team Studies

- JPL A-Team (Architecture Team) performs concurrent mission studies at the earliest stages of formulation



Graphic from Ziemer, J.K., et al., "Exploring Mission Concepts with the JPL Innovation Foundry A-Team," AIAA-2013-5431

A-Team Study Objectives

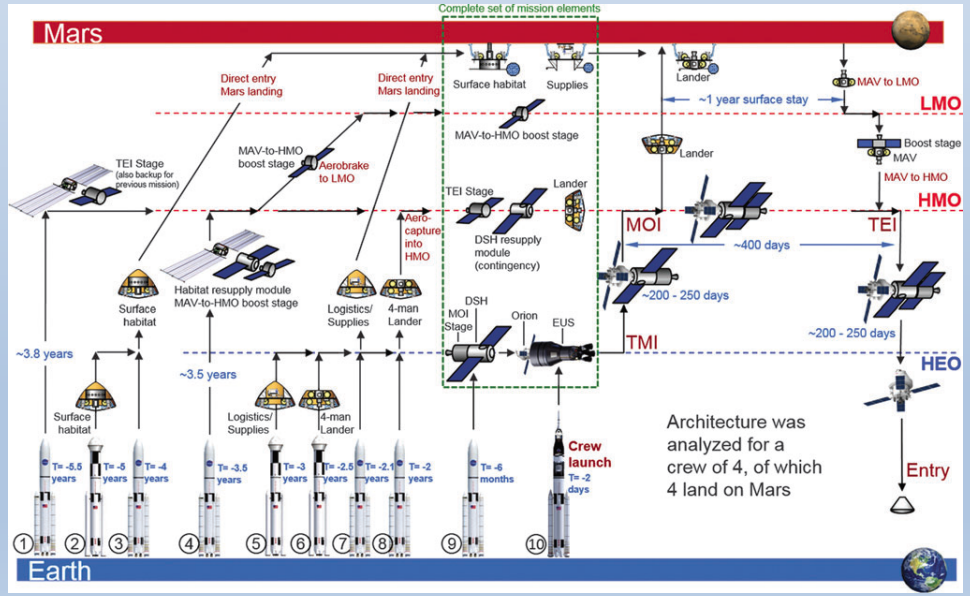
- Recognizing (a) the possibility of a shift back to the moon and (b) the growing capabilities and access to capital of commercial space, develop conceptual lunar architectures that could simultaneously:
  - Provide “living on another world” experience;
  - Be affordable;
  - Offer truly significant commercial and international partnering opportunities;
  - Lead to and flow into human missions to Mars in the 2030s/2040s.
- Capture architectures in a systematic way
- Assess affordability concurrently, and in doing so, demonstrate how affordability assessments could enhance the architecture definition process.

Determining Affordability

- Different views as to what that means
- NRC 2014 Report, "*Pathways to Exploration: Rationales and Approaches For a U.S. Program of Human Space Exploration*," used a "sand chart" approach
  - Could a human mission be done within NASA's current human spaceflight budget?
  - Could it be done within NASA's current human spaceflight budget that grows to maintain current purchasing power?
- NRC 2014 Report sand charts were based on a methodology and cost data developed by the Aerospace Corporation
  - Methodology has three cost "flavors"
  - Cost estimates from public sources only
  - Needs a multi-faceted description of the architecture

Building the Sand Chart—Defining an Architecture

Vehicles	# Vehicles per Mission
Orion	1
SLS	6
SEP Tug	2
Deep Space Habitat	1
In-Space Chemical Propulsion Stages	3
Mars Lander	1



HSF Architectures Can Be Complex

- A well-defined architecture framework is useful in abstracting essential information from the underlying complexity
- DoDAF-inspired Human Spaceflight Architecture Model (HSFAM)* artifacts:

Name	Description of Architectural Content	Classes, Types, and Subtypes
Operational Nodes	Spatial locations in the solar system; locus of an operational function or activity	Surface locations (terrestrial and planetary); orbits; Lagrange points
Systems	Notional objects that fulfill a function; a hardware and/or software build	Based on broad system purposes, e.g., surface mobility, habitation
Operational Functions	Activities that transform inputs (resources) into outputs (other resources or end products), or change their state	Based on broad functional areas, e.g., mission operations, etc.
Milestones	Time-stamped identification of significant changes; milestones are four-dimensional as the spatial location (operational node) is also included	Based on capability achieved, e.g., initial operational capability (IOC)
Measures	Measurable (quantifiable) properties or attributes of interest	Mass, cost, quantity, etc.
Standards	Applicable technical, operational or business standards and rules	ISO, ANSI, Community of Practice (CoP), government-unique, etc.
Flight Types	Arcs (or edges) between operational nodes that form a feasible network along which systems can move	
Flights	Time-stamped assignment of flight types	

*Available at http://hdl.handle.net/2014/45707

A-Team's Conceptual Lunar Architecture

- Initial focus on a Human Lunar Return (HLR) as soon as practical
  - Living on Another World" experience and experimentation
  - Maintain public interest
  - Being first has value.
- Affordability is a budgetary imperative.
- NASA's role: manage the magnitude of public investment while fostering a private sector cislunar economy through strategic investments such as:
  - Engaging in science and exploration (e.g., Lewis and Clark)
  - Reducing economic risks and resolving some technical uncertainties to create tipping points and real options for space entrepreneurs
  - Performing R&D/DDT&E and first buys of basic systems/services
  - Building public (lunar) infrastructure (e.g., roads, navigation aids, basic communications, logistics nodes, operational knowledge/de-confliction)
  - Acting as an anchor tenant.

A-Team's Conceptual Lunar Architecture

- "Minimal Moon"
  - Sufficient public investment to signal serious intentions regarding lunar exploration and development to commercial investors, but
  - Careful not to displace private investments.
- Role of SLS/Orion
  - Extensive use for both lunar and Mars portions of the architecture
  - Flights rates ramp up: 1/year in first-half 2020s to 2/year in second half, and then to 2.5/year in 2030s/2040s for Mars missions.
  - SLS Block 2 available in 2028
- Are public goals for human space exploration being met?
  - Are private investors coming on board?
  - Are we ready to go to Mars?
- On- and off-ramps (and periodic decision points)

The Adjoined "Minimal Mars" Architecture

- Response to NRC 2014 Report
  - Minimize the number of new system developments
  - Use of high TRL technologies
- First presentation of architecture (without costing) at AIAA Space 2014 (August 7, 2014)
- Minimal Mars presented at Humans Orbiting Mars (Mar. 31, 2015), H2M Summit (May 5, 2015), and published in *New Space* (June 2015)
- Revised and re-costed Minimal Mars architecture (July 2016) for OIG Report, "NASA's Plans for Human Exploration Beyond Low Earth Orbit," OIG-17-017, April 2017
- Continued refinement and presented at H2M Summit (May 8, 2018)
- Combined A-Team architecture (Minimal Moon + Minimal Mars) presented at IEEE Aerospace Conference, March 2018

Defining an Architecture—Dance Card View (2021-2035)

SLS/Orion Segment—Largely Lunar Focused

SLS Launches	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Flight Type		SLS Blk-1b		SLS Blk-1b		SLS Blk-1b	SLS Blk-1b	SLS Blk-2		SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	
Flight Name Orion		EM-2 (8-21 days)		EM-3 (8-21 days)		EM-4 (8-21 days)	EM-5	EM-6		EM-7	EM-8	EM-9	EM-10	EM-11	
Co-manifested NASA															
Co-manifested IP				Comm Orbiter-1		Comm Orbiter-2 (for redundancy and full LSP coverage)									
Flight Type					SLS Blk-1b	SLS Blk-1b	SLS Blk-1b	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	
Flight Name NASA Cargo					Habitat-1 Habitat (>5000 kg) with A-AMA/ tunnel; ATHLETE mobility unit	DAV-1 DAV test (uncrewed)	DAV-2 (HLR) Unpressurized small rover (4 astronauts) with human lander	DAV-3 Unpressurized small rover (4 astronauts) with human lander	Habitat-2 Habitat (>5000 kg) with A-AMA/ tunnel; ATHLETE mobility unit	DAV-4	DAV-5	DAV-6 Unpressurized small rover (4 astronauts) with human lander	DAV-7 Unpressurized small rover (4 astronauts) with human lander	DAV-8	
Flight Type													SLS Blk-2	SLS Blk-2	
Flight Name IP Cargo NASA Cargo													Phobos SEP #1 TEI-4 Phobos Transfer Stages 100 kW SEP	Phobos SEP #2 100 kW SEP and Phobos Lander	
Flight Type															
Flight Name NASA Cargo															
Planetary Missions			Europa Clipper on SLS Blk-1b		Possible Europa Lander on SLS Blk-1b				Possible mission on SLS Blk-2						Possible mission on SLS Blk-2
Crew Operations		EM-1 (uncrewed mission) in 2019. EM-2 crew on a free return trajectory delivers		EM-3 crew monitors surface deployments from NRLO.		EM-4 crew performs a dress rehersal for HLR with uncrewed human lunar DAV using stretch version of Orion Service Module (SM); this SM is used on all subsequent lunar missions	EM-5 crew performs 7-14 day surface mission to include outfitting habitat module as needed and assessing previous deployments	EM-6 crew performs 14-28 days surface mission and continues to outfit habitat module with longer-term life support systems; performs repairs as needed		EM-7 crew performs 28-60 day surface mission; connects 2nd habitat and 2nd solar power system; prepares for pressurized crew rover and performs repairs as needed	EM-8 crew performs 28-60 day surface mission; completes integration and checkout of pressurized crew rover and performs repairs as needed	EM-9 crew of government and possibly commercial astronauts perform 60-90 day surface mission	EM-10 crew of government and possibly commercial astronauts perform 60-90 day surface mission	EM-11 crew of government and possibly commercial astronauts perform 60-90 day surface mission; connects 3rd solar power system; deploys longer range communication/ navigation aids	
Crew Return Vehicle		EM-2 Orion		EM-3 Orion		EM-4 Orion	EM-5 Orion	EM-6 Orion		EM-7 Orion	EM-8 Orion	EM-9 Orion	EM-10 Orion	EM-11 Orion	

Pre-decisional. For discussion purposes only.

Defining an Architecture—Dance Card View (2021-2035)

Commercial Segment—Largely Lunar and LEO Gateway Focused

Commercial Launches	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Flight Type			Medium ELV	Heavy ELV		Heavy ELV		Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	
Flight Name			RP-I	Lunar Lander-1		Lunar Lander-2		Lunar Lander-3	Lunar Lander-4	Lunar Lander-5	Lunar Lander-6	Lunar Lander-7	Lunar Lander-8	Lunar Lander-9	
Cargo Manifested			Resource Prospector I mission (tele-operated from Earth)	Stationary solar power system with cables; ATHLETE mobility unit to transport surface components		Pressurized logistics module (PLM) to be linked with habitat; contains supplies and tools for initial habitat setup; Bulldozing and sintering tools for ATHLETE; navigation aids		Pressurized logistics module (PLM) to be linked with habitat; contains supplies, spares, and scientific equipment; Resource Prospector (RP) II	Pressurized logistics module (PLM) to be linked with habitat; contains supplies, spares, and scientific equipment; solar power, cables; navigation aids	Pressurized logistics module (PLM) to be linked with habitat; contains supplies and spare or replacement ATHLETE	Pressurized crew cabin and CMC (4 astronauts); rover contains supplies, spares, and scientific equipment; connects to habitat with A-AMA/ tunnel	Pressurized logistics module (PLM) to be linked with habitat; contains supplies, spares, and scientific equipment; Li-ion batteries or RFCs for rovers	Pressurized logistics module (PLM) to be linked with habitat; contains supplies, spares, and scientific equipment; Li-ion batteries or RFCs for rovers	Pressurized logistics module (PLM) to be linked with habitat; contains supplies, spares, and scientific equipment; replacement solar power, cables; L-R navigation aids	
Flight Type					Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV
Flight Name					Possible commercial lunar landing missions	Possible commercial lunar landing missions	Possible commercial lunar landing missions	Possible commercial lunar landing missions	Possible commercial lunar landing missions	Mars DSH to LEO *LEO PG Systems*	Possible commercial lunar landing missions	Uncrewed 1/2-scale Mars lander test	Possible commercial lunar landing missions	Possible commercial lunar landing missions	Possible commercial lunar landing missions
Cargo Manifested										Protoflight DSH unit with 40kW pwr/prop bus to LEO					
Flight Type										Medium ELV	Medium ELV	Heavy ELV	Medium ELV	Medium ELV	Medium ELV
Flight Name										Logistics re-supply (mod Cygnus)	Logistics re-supply (mod Cygnus)	IP Chem Stage Test	Logistics re-supply (mod Cygnus)	Logistics re-supply (mod Cygnus)	Logistics re-supply (mod Cygnus)
Cargo Manifested															
Flight Type										Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV
Flight Name										LEO Trng Flt-1	LEO Trng Flt-2	LEO Trng Flt-3	LEO Trng Flt-4	LEO Trgn Flt-5	LEO Trgn Flt-6
Cargo Manifested															
Comments			Could be landed by a Lunar Lander as part of a multi-payload mission		Habitat delivered with large descent stage that serves as a protoflight DAV	Could possibly do Human Lunar Return (HLR) on EM-4		RP II can be operated from the moon or Earth		3-month mission; Cygnus modified with Orion docking adaptor	6-month mission; Cygnus modified with Orion docking adaptor	1/2-scale test at Mars could be performed by a single SLS Blk-2	9-month mission; Cygnus modified with Orion docking adaptor	9-month mission; Cygnus modified with Orion docking adaptor	9-month mission; Cygnus modified with Orion docking adaptor

Pre-decisional. For discussion purposes only.

Defining an Architecture—Dance Card View (2036-2050)

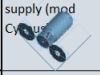
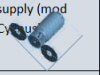
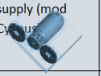
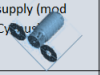
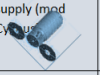
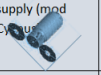
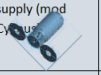
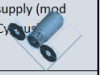
SLS/Orion Segment—Largely Mars Focused

SLS Launches	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
Flight Type	SLS Blk-2	SLS Blk-2				SLS Blk-2				SLS-Blk-2				SLS Blk-2	
Flight Name Orion	EM-12 (Lander test crew at moon)	EM-13 (Phobos crew)				EM-14 (Mars-1 crew)				EM-15 (Mars-2 crew)				EM-16 (Mars-3 crew)	
Co-manifested NASA															
Co-manifested IP															
Flight Type			SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2
Flight Name NASA Cargo			Mars SEP #2 DSH-based logistics module and 100 kW SEP	Mars Lander #1 Mars DAV	Mars Cargo #1 Mars Surface Cargo Lander	EUS #2 EUS for Mars Surface Cargo Lander TMI	Mars SEP #4 DSH-based logistics module and 100 kW SEP	Mars Hab #1 Mars Surface Habitat	Mars Cargo #2 Mars Surface Cargo Lander	EUS #5 EUS for Mars Surface Cargo Lander TMI	Mars SEP #6 DSH-based logistics module and 100 kW SEP	Mars Hab #2 Mars Surface Habitat	Mars Cargo #3 Mars Surface Cargo Lander	EUS #8 EUS for Mars Surface Cargo Lander TMI	Mars SEP #8 DSH-based logistics module and 100 kW SEP
Flight Type	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2	SLS Blk-2
Flight Name IP Cargo NASA Cargo	Mars lander test at moon Mars DAV	Phobos DSH MOI Stage Phobos DSH	Mars SEP #1 TEI and MAV Boost Stages 100 kW SEP	EUS #1 EUS for Mars DAV TMI	Mars SEP #3 TEI and MAV Boost Stages 100 kW SEP	Mars DSH #1 MOI Stage Mars DSH	Mars Lander #2 Mars DAV	EUS #3 EUS for Mars DAV TMI	Mars SEP #5 TEI and MAV Boost Stages 100 kW SEP	Mars DSH #2 MOI Stage Mars DSH	Mars Lander #3 Mars DAV	EUS #6 EUS for Mars DAV TMI	Mars SEP #7 TEI and MAV Boost Stages 100 kW SEP	Mars DSH #3 MOI Stage Mars DSH	Mars Lander #4 Mars DAV
Flight Type								SLS Blk-2				SLS Blk-2			
Flight Name NASA Cargo								EUS #4 EUS for Mars Surface Hab TMI				EUS #7 EUS for Mars Surface Hab TMI			
Planetary Missions															
Crew Operations	EM-12 crew conducts a full-scale test of the Mars DAV at the moon	EM-13 crew rendezvous and docks with the Phobos DSH; TMI is performed by the crew launch EUS; MOI is performed by the IP-provided chemical stage				EM-14 crew rendezvous and docks with the Mars DSH; TMI is performed by the crew-launch EUS; MOI is performed by the IP-provided chemical stage; Mars-1 is an opposition class (surface stay ~24 days) mission				EM-15 crew rendezvous and docks with the Mars DSH; TMI is performed by the crew-launch EUS; MOI is performed by the IP-provided chemical stage; Mars-2 is an conjuction class (surface stay >1 year) mission				EM-16 crew rendezvous and docks with the Mars DSH; TMI is performed by the crew-launch EUS; MOI is performed by the IP-provided chemical stage; Mars-3 is an conjuction class (surface stay >1 year) mission	
Crew Return Vehicle														EM-13 Orion	

Pre-decisional. For discussion purposes only.

Defining an Architecture—Dance Card View (2036-2050)

Commercial Segment—Largely LEO Gateway Focused

Commercial Launches	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
Flight Type															
Flight Name															
Cargo Manifested															
Flight Type	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV	Heavy ELV
Flight Name															
Cargo Manifested	Possible commercial lunar landing missions	Possible commercial lunar landing missions	Possible commercial lunar landing missions	Possible commercial lunar landing missions	Possible commercial lunar landing missions	Possible commercial lunar landing missions	Possible commercial lunar landing missions	Possible commercial lunar landing missions	Possible commercial lunar landing missions	Possible commercial lunar landing missions	Possible commercial lunar landing missions	Possible commercial lunar landing missions	Possible commercial lunar landing missions	Possible commercial lunar landing missions	Possible commercial lunar landing missions
Flight Type	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV
Flight Name	Logistics re-supply (mod Cygnus	Logistics re-supply (mod Cygnus	Logistics re-supply (mod Cygnus	Logistics re-supply (mod Cygnus	Logistics re-supply (mod Cygnus	Logistics re-supply (mod Cygnus	Logistics re-supply (mod Cygnus	Logistics re-supply (mod Cygnus	Logistics re-supply (mod Cygnus	Logistics re-supply (mod Cygnus	Logistics re-supply (mod Cygnus	Logistics re-supply (mod Cygnus	Logistics re-supply (mod Cygnus	Logistics re-supply (mod Cygnus	Logistics re-supply (mod Cygnus
Cargo Manifested															
Flight Type	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV	Medium ELV
Flight Name	LEO Trgn Flt-7	LEO Trgn Flt-8	LEO Trgn Flt-9	LEO Trgn Flt-10	LEO Trgn Flt-11	LEO Trgn Flt-12	LEO Trgn Flt-13	LEO Trgn Flt-14	LEO Trgn Flt-15	LEO Trgn Flt-16	LEO Trgn Flt-17	LEO Trng Flt-18	LEO Trng Flt-19	LEO Trng Flt-20	LEO Trng Flt-21
Cargo Manifested															
Comments	9-month mission; Cygnus modified with Orion docking adaptor	9-month mission; Cygnus modified with Orion docking adaptor	9-month mission; Cygnus modified with Orion docking adaptor	9-month mission; Cygnus modified with Orion docking adaptor	9-month mission; Cygnus modified with Orion docking adaptor	9-month mission; Cygnus modified with Orion docking adaptor	9-month mission; Cygnus modified with Orion docking adaptor	9-month mission; Cygnus modified with Orion docking adaptor	9-month mission; Cygnus modified with Orion docking adaptor	9-month mission; Cygnus modified with Orion docking adaptor	9-month mission; Cygnus modified with Orion docking adaptor	9-month mission; Cygnus modified with Orion docking adaptor	9-month mission; Cygnus modified with Orion docking adaptor	9-month mission; Cygnus modified with Orion docking adaptor	9-month mission; Cygnus modified with Orion docking adaptor

Costing the A-Team Architecture

- Applied the Aerospace Corporation methodology.
  - Generally retained Aerospace cost data for Mars portion
  - Cost data for lunar surface systems from Constellation Program estimates
  - SEP costs from ARM
  - Updated actual costs for on-going programs
  - For the contemporary Lunar Module (LM) converged three sources of data
- International contributions for lunar and Mars portions
  - Upgraded Orion Service Module (SM)
  - Lunar communications infrastructure
  - Chem stages (MOI, TEI, MAV-to-HMO Boost)
- Made significant improvements in the Excel ©/VBA software, the Programmatic Cost Tool (PCT).
  - Captured the relevant Dance Card information in a formal architecture framework/data model (HSFAM) digestible by the PCT
  - Inputs organized in just three tables: Systems, Flight Types, Flights

Programmatic Cost Tool Inputs—Flight Types Table (Partial)

Flight Type ID	Flight Type Name	Partner Name	Crew Size	LV System ID	Launch Vehicle System Short Name	Primary Payload System ID	Primary Payload System Short Name	Primary Payload Qty Manifested	Secondary Payload System ID	Secondary Payload System Short Name	Secondary Payload Qty Manifested
1	Uncrewed Exploration Mission	NASA	0	1	SLS (Blk 1A)	3	Orion (Blk 1)	1			
2	SEP Demo	NASA	0	47	Vulcan-ACES	30	50 kW Pwr/Prop	1			
3	Exploration Mission	NASA	4	2	SLS (Blk 1B)	3	Orion (Blk 1)	1			
4	Dedicated ISRU Mission	NASA	0	45	Glenn	40	RP	1			
5	Lunar Cargo Mission-A	Comm	0	46	Falcon-9H	32	LCL-Hvy	1	53	16kW SPU	1
6	Lunar Cargo Mission-C	Comm	0	46	Falcon-9H	32	LCL-Hvy	1	76	Lunar-PLM	1
7	Exploration Mission w/CommSat	NASA	0	2	SLS (Blk 1B)	3	Orion (Blk 1)	1	26	LCS	1
8	Lunar Habitat Deployment	NASA	0	2	SLS (Blk 1B)	6	LunarHab	1	29	Lunar DM	1
9	Lunar Habitat Deployment+	NASA	0	5	SLS (Blk 2)	6	LunarHab	1	29	Lunar DM	1
10	Lunar Cargo Mission-B	Comm	0	46	Falcon-9H	32	LCL-Hvy	1	76	Lunar-PLM	1
11	Lunar Lander Mission	NASA	0	2	SLS (Blk 1B)	28	Lunar AM	1	29	Lunar DM	1
12	Lunar Crewed Mission	NASA	4	2	SLS (Blk 1B)	3	Orion (Blk 1)	1			
13	Lunar Lander Mission	NASA	0	2	SLS (Blk 1B)	28	Lunar AM	1	29	Lunar DM	1
14	Lunar Lander Mission+	NASA	0	5	SLS (Blk 2)	28	Lunar AM	1	29	Lunar DM	1
15	Lunar Crewed Mission+	NASA	4	5	SLS (Blk 2)	3	Orion (Blk 1)	1			
16	Lunar Cargo Mission-ISRU	Comm	0	46	Falcon-9H	32	LCL-Hvy	1	76	Lunar-PLM	1
17	Lunar Cargo Mission-Batt	Comm	0	46	Falcon-9H	32	LCL-Hvy	1	76	Lunar-PLM	1
18	Lunar Cargo Mission-SPU	Comm	0	46	Falcon-9H	32	LCL-Hvy	1	76	Lunar-PLM	1
19	Lunar Cargo Mission-PLR	Comm	0	46	Falcon-9H	32	LCL-Hvy	1	38	Press LR	1
20	Lunar Lander Mission-LM	NASA	0	5	SLS (Blk 2)	28	Lunar AM	1	29	Lunar DM	1
21	Protoflight DSH Mission	NASA	0	46	Falcon-9H	12	DSH Proto	1	30	50 kW Pwr/Prop	1
22	LEO Log Resupply Mission	NASA	0	44	ELV	80	Cygnus	1			
23	LEO Trng Mission	NASA	4	43	CTV	83	Dragon 2	1			
24	Half-Scale Mars EDL Test	NASA	0	46	Falcon-9H	66	1/2-Mars DS	1			
25	Chem Stage Test	IP	0	78	Ariane 6	8	Chem Stages	1			
26	SEP100+ChemProp (TEI+MOT)	NASA	0	5	SLS (Blk 2)	10	Mars SEPs	1	8	Chem Stages	2
27	SEP100+PhoHab	NASA	0	5	SLS (Blk 2)	10	Mars SEPs	1	9	PhobosHab	1
28	Mars Crewed Mission+	NASA	6	5	SLS (Blk 2)	3	Orion (Blk 1)	1			
29	DSH+ChemProp (MOI)	NASA	0	5	SLS (Blk 2)	13	DSH	1	8	Chem Stages	1
30	Mars Lander Mission	NASA	0	5	SLS (Blk 2)	15	Mars DS	1	14	Mars AS	1
31	EUS for TMI	NASA	0	5	SLS (Blk 2)	22	TMI Kit	1			
32	Mars Surf Cargo Mission-A	NASA	0	5	SLS (Blk 2)	15	Mars DS	1	57	Mars Surf Sys I	1
33	Mars Surf Cargo Mission-B	NASA	0	5	SLS (Blk 2)	15	Mars DS	1	58	Mars Surf Sys II	1
34	Mars Habitat Deployment	NASA	0	5	SLS (Blk 2)	15	Mars DS	1	11	MarsHab	1
35	SEP100+DSH-Based PLM	NASA	0	5	SLS (Blk 2)	10	Mars SEPs	1	20	DSH-PLM	1
36	Mars Surf Cargo Mission-C	NASA	0	5	SLS (Blk 2)	15	Mars DS	1	54	Kilopower-10kW	2

Programmatic Cost Tool Input—
Flights Table (First 40 of 111 Records)

Flights Table

Flight ID	Flight Name	Flight Type ID	Flight Type Name	Mission Group Name	Destination Node	Nominal Flight Start Date (FY)	Nominal Flight End Date	Include In Ops Profile (T/F)	Data Source/Comments
1	EM-1	1	Uncrewed Exploration Mission	Uncrewed	LFRO	2019	2019	TRUE	Min Moon
2	EM-2	3	Exploration Mission	Cislunar Shakedown	LFRO	2022	2022	TRUE	Min Moon
3	Resource Prospector-1	4	Dedicated ISRU Mission	Lunar Surface	LSP	2023	2023	TRUE	Min Moon
4	EM-3	7	Exploration Mission w/CommSat	Cislunar	HELO	2024	2024	TRUE	Min Moon
5	Lunar Lander-1	5	Lunar Cargo Mission-A	Lunar Surface	LSPO	2024	2024	TRUE	Min Moon
6	Habitat-1	8	Lunar Habitat Deployment	Lunar Surface	LSPO	2025	2025	TRUE	Min Moon
7	EM-4	7	Exploration Mission w/CommSat	Cislunar	LLO	2026	2026	TRUE	Min Moon
8	DAV-1	11	Lunar Lander Mission	Lunar Surface	LSPO	2026	2026	TRUE	Min Moon
9	Lunar Lander-2	10	Lunar Cargo Mission-B	Lunar Surface	LSPO	2026	2026	TRUE	Min Moon
10	EM-5	12	Lunar Crewed Mission	Cislunar	LLO	2027	2027	TRUE	Min Moon
11	DAV-2 (HLR)	13	Lunar Lander Mission	Lunar Surface	LSPO	2027	2027	TRUE	Min Moon
12	EM-6	15	Lunar Crewed Mission+	Cislunar	LLO	2028	2028	TRUE	Min Moon
13	DAV-3	14	Lunar Lander Mission+	Lunar Surface	LSPO	2028	2028	TRUE	Min Moon
14	Lunar Lander-3	16	Lunar Cargo Mission-ISRU	Lunar Surface	LSPO	2028	2028	TRUE	Min Moon
15	Habitat-2	9	Lunar Habitat Deployment+	Lunar Surface	LSPO	2029	2029	TRUE	Min Moon
16	Lunar Lander-4	18	Lunar Cargo Mission-SPU	Lunar Surface	LSPO	2029	2029	TRUE	Min Moon
17	EM-7	15	Lunar Crewed Mission+	Cislunar	LLO	2030	2030	TRUE	Min Moon
18	DAV-4	20	Lunar Lander Mission-LM	Lunar Surface	LSPO	2030	2030	TRUE	Min Moon
19	Lunar Lander-5	6	Lunar Cargo Mission-C	Lunar Surface	LSPO	2030	2030	TRUE	Min Moon
20	EM-8	15	Lunar Crewed Mission+	Cislunar	LLO	2031	2031	TRUE	Min Moon
21	DAV-5	20	Lunar Lander Mission-LM	Lunar Surface	LSPO	2031	2031	TRUE	Min Moon
22	Lunar Lander-6	19	Lunar Cargo Mission-PLR	Lunar Surface	LSPO	2031	2031	TRUE	Min Moon
23	EM-9	15	Lunar Crewed Mission+	Cislunar	LLO	2032	2032	TRUE	Min Moon
24	DAV-6	14	Lunar Lander Mission+	Lunar Surface	LSPO	2032	2032	TRUE	Min Moon
25	Lunar Lander-7	17	Lunar Cargo Mission-Batt	Lunar Surface	LSPO	2032	2032	TRUE	Min Moon
26	EM-10	15	Lunar Crewed Mission+	Cislunar	LLO	2033	2033	TRUE	Min Moon
27	DAV-7	14	Lunar Lander Mission+	Lunar Surface	LSPO	2033	2033	TRUE	Min Moon
28	Lunar Lander-8	17	Lunar Cargo Mission-Batt	Lunar Surface	LSPO	2033	2033	TRUE	Min Moon
29	EM-11	15	Lunar Crewed Mission+	Cislunar	LLO	2034	2034	TRUE	Min Moon
30	DAV-8	20	Lunar Lander Mission-LM	Lunar Surface	LSPO	2034	2034	TRUE	Min Moon
31	Lunar Lander-9	18	Lunar Cargo Mission-SPU	Lunar Surface	LSPO	2034	2034	TRUE	Min Moon
32	Protoflight DSH to LEO	21	Protoflight DSH Mission	LEO Training	LEO	2030	2030	TRUE	Min Mars
33	Logistics Flt-1	22	LEO Log Resupply Mission	LEO Training	LEO	2030	2030	TRUE	Min Mars
34	Trng Flt-1	23	LEO Trng Mission	LEO Training	LEO	2030	2030	TRUE	Min Mars
35	Logistics Flt-2	22	LEO Log Resupply Mission	LEO Training	LEO	2031	2031	TRUE	Min Mars
36	Trng Flt-2	23	LEO Trng Mission	LEO Training	LEO	2031	2031	TRUE	Min Mars
37	Half-Scale Mars EDL Test	24	Half-Scale Mars EDL Test	Mars Test	Mars Surface	2032	2032	TRUE	Min Mars
38	Chem Prop Stage Test	25	Chem Stage Test	Mars Test	Solar Orbit	2032	2032	TRUE	Min Mars
39	Trng Flt-3	23	LEO Trng Mission	LEO Training	LEO	2032	2032	TRUE	Min Mars
40	Phobos SEP-1	26	SEP100+ChemProp (TEI+MOT)	Phobos	Mars System	2033	2036	TRUE	Min Mars

Use of a Formal Architecture Framework—Building the Sand Chart

Systems Table

System development, production, and sustaining cost estimates, and durations, with anticipated cost sharing arrangements

Systems Table

Flight Types Table

Flight Type definition

Flights Table

Schedule of flights by Flight Type

Life Cycle Cost Model

NASA New Start Inflation Index

Inflation Table

Pre-decisional. For discussion purposes only.

Building the Sand Chart—The Life Cycle Cost Model

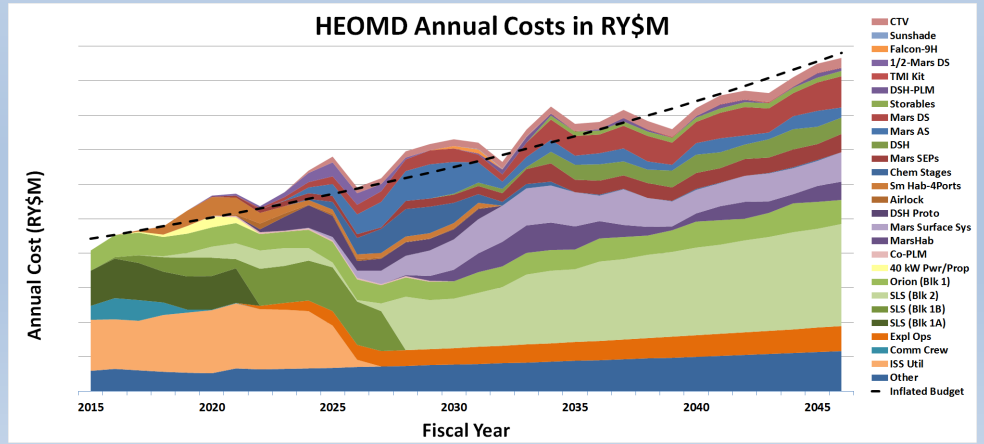
Conceptual Architecture

Life Cycle Cost Model

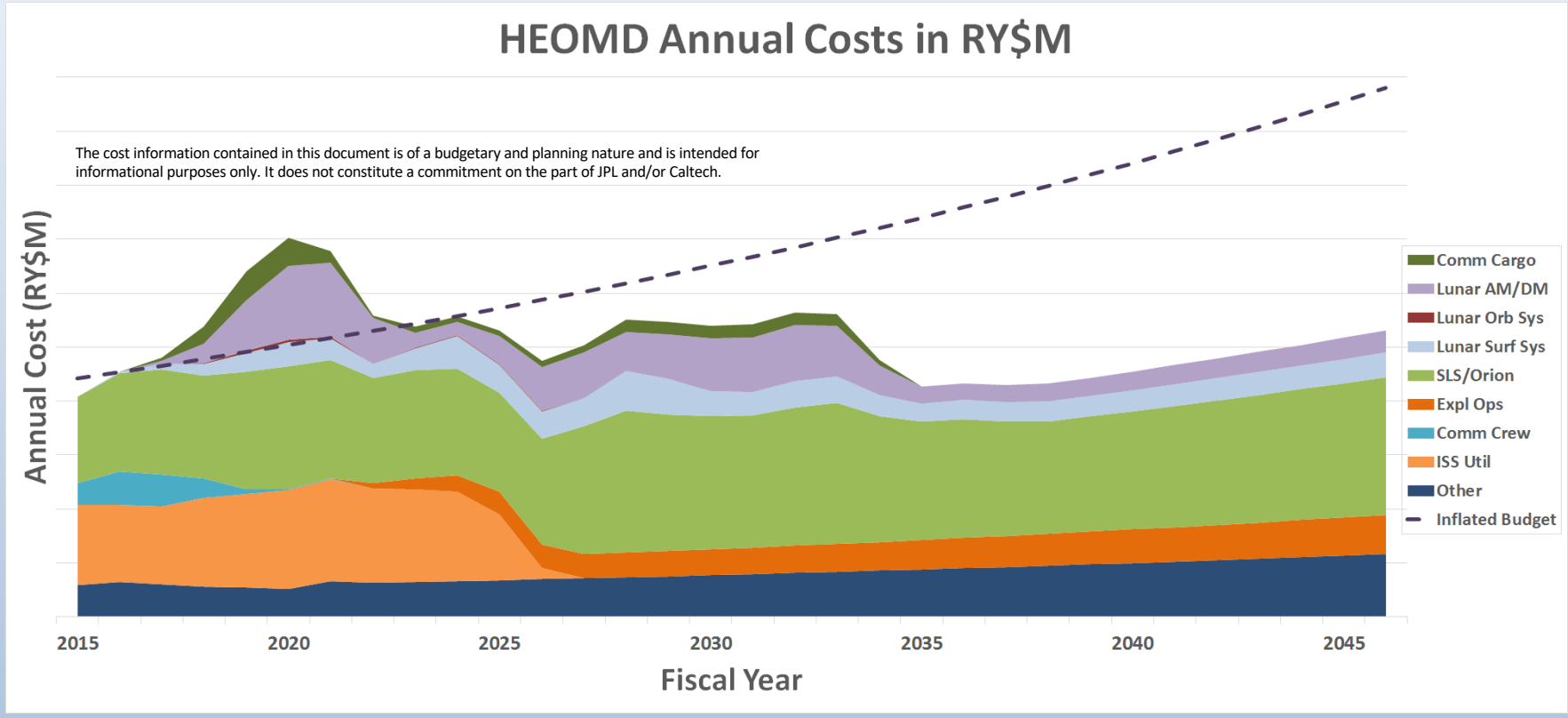
Design, Development, Test and Evaluation (DDT&E) Cost Model

Production Cost Model

Operations and Support (O&S) Cost Model

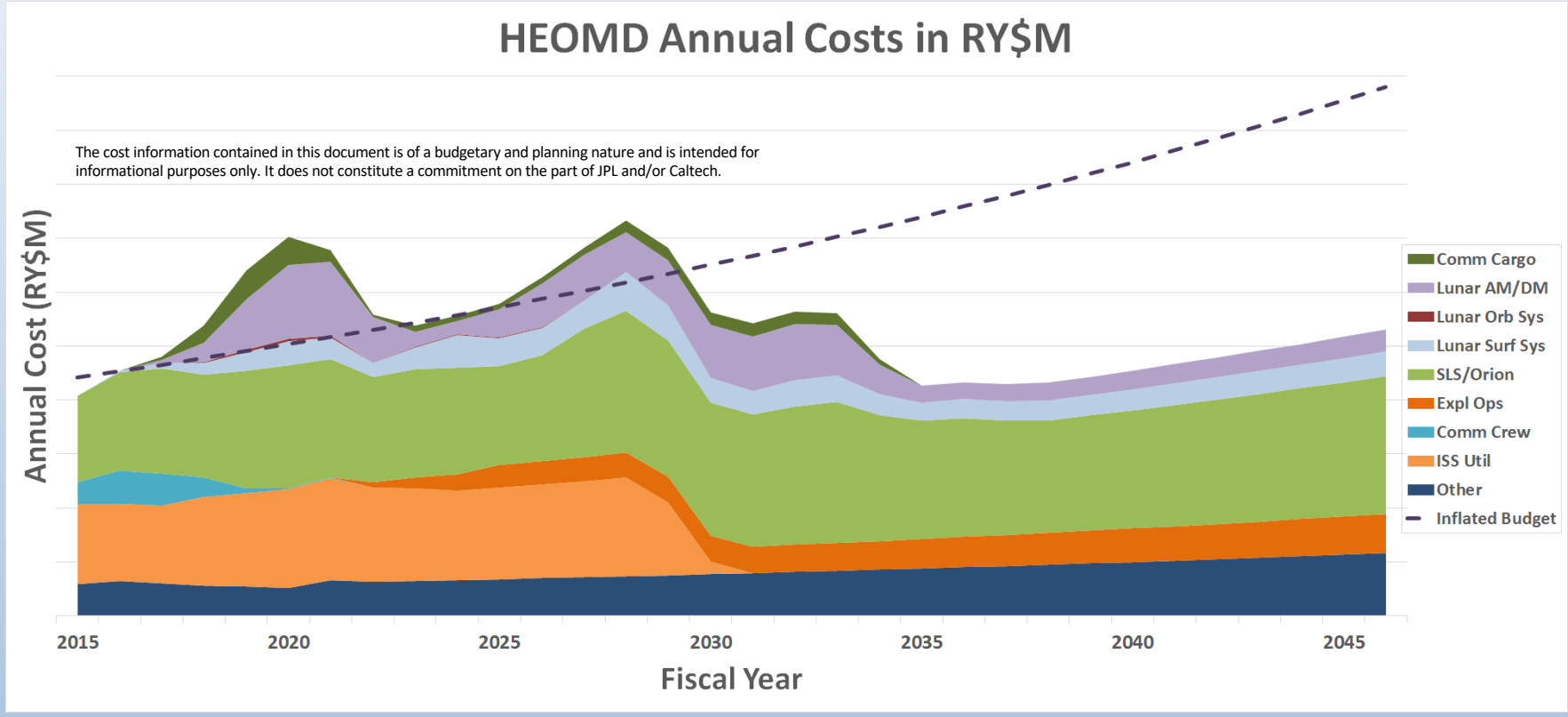


A-Team Minimal Moon with HLR in 2027



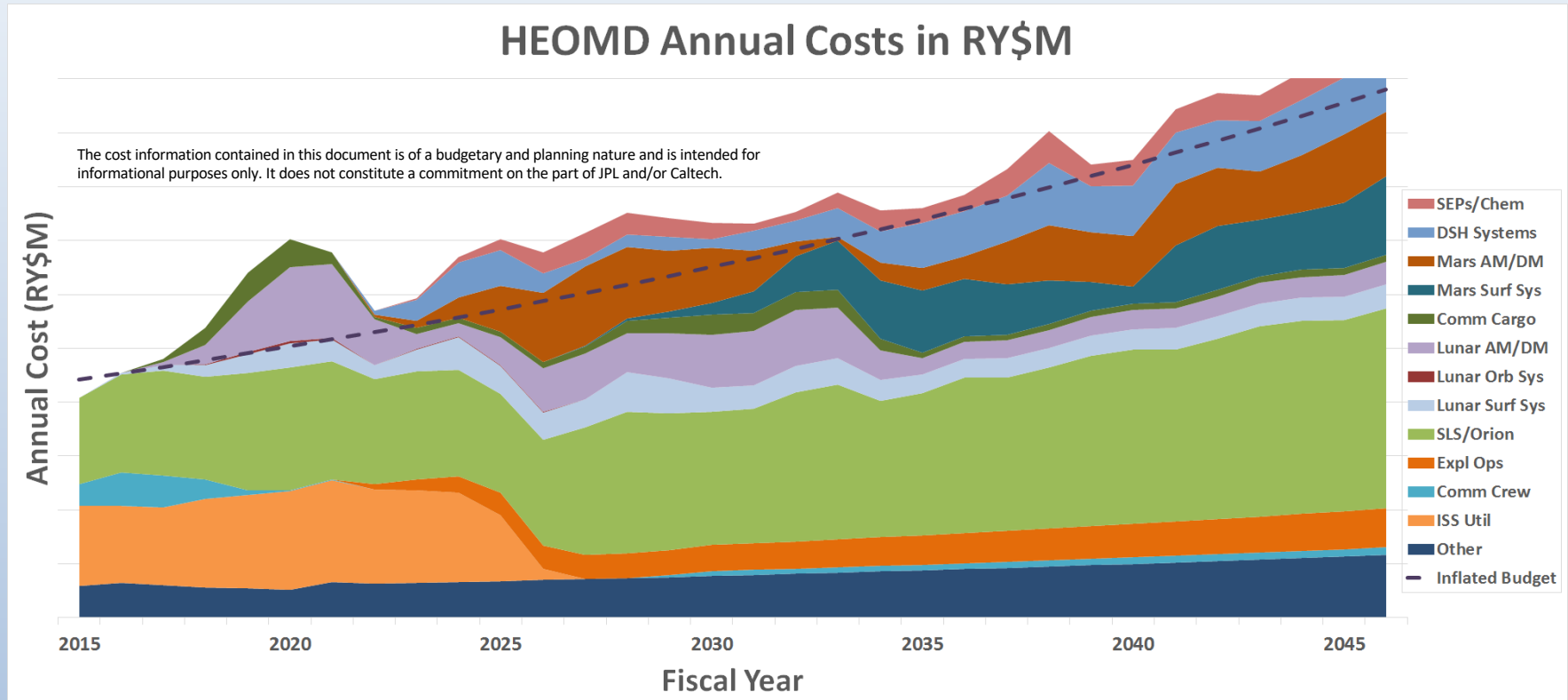
Scenario Name	Human Lunar Return	First Mars System Mission	First Mars Landing	ISS EOPM
Minimal Moon	2027	N/A	N/A	2024

A-Team Minimal Moon with HLR in 2027



Scenario Name	Human Lunar Return	First Mars System Mission	First Mars Landing	ISS EOPM
Minimal Moon	2027	N/A	N/A	2028

A-Team Study Minimal Moon with HLR in 2027 + Minimal Mars with First Mars Mission in 2037



Scenario Name	Human Lunar Return	First Mars System Mission	First Mars Landing	ISS EOPM
Minimal Moon + Minimal Mars	2027	2037	2041	2024

Key Messages

- The capability to integrate system-of-systems architecting, programmatics, and affordability assessments could significantly benefit HEOMD architecture teams and NASA/OCFO strategic planning.
  - Enables affordability to be part of the trade space exploration
  - Allows the Exploration Architect to see the effects on affordability of adding/removing missions, re-phasing missions, and/or including P-P-P and International Partner contributions.
- This capability is intended for long-range planning purposes (>5 yrs).
  - Useful for architecture and pathway comparisons, not for budget decisions.
- With personnel trained in its use, the affordability assessment capability can be embedded within HEOMD and the NASA/OCFO as needed.
- Final thought

REFERENCES AND BACKUP

Key References

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- Shishko, R., "Human Spaceflight Architecture Model (HSFAM) Data Dictionary, v.1.0," on-line document, September 2016, available at http://hdl.handle.net/2014/45707
- NASA Office of the Inspector General, "NASA's Plans for Human Exploration Beyond Low Earth Orbit," OIG-17-017, April 2017
- Shishko, R., Price, H., Wilcox, B., et al., "An Affordable Lunar Architecture Emphasizing Commercial and International Partnering Opportunities," IEEE Aerospace Conference, Big Sky, MT, March 5-8, 2018
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NRC "Pathways" Report

Section 4.4, p. 175, Key Results

"With current flat or even inflation-adjusted budget projections for human spaceflight, there are no viable pathways to Mars.

a. A continuation of flat budgets for human spaceflight is insufficient for NASA to execute any pathway to Mars and limits human spaceflight to LEO until after the end of the ISS program.

b. Even with a NASA human spaceflight budget adjusted for inflation, technical and operational risks do not permit a viable pathway to Mars.

c. The currently planned crewed flight rate is far below the flight rate of past human spaceflight programs.

d. Increasing NASA's budget to allow increasing the human spaceflight budget by 5 percent per year would enable pathways with potentially viable mission rates, greatly reducing technical, cost, and schedule risk."

System Cost Profile Generation

- Current systems in development use current budget data for development costs and a standard beta spreader (40/60) for future production costs
- Development and production cost profiles for future systems were generated using a standard beta spreader (40/60)